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## Application of Linearised Amplifiers in Adaptive Antennas

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**Abstract** - The use of adaptive antennas in mobile communications base stations is self-explanatory. It offers the potential of increased spectrum efficiency, extended range of coverage and reduced delay spread. However, one major concern for adaptive antenna system is the non-linearity effects of the RF/IF chain upon digital baseband beam forming network. This contribution investigates these effects on the performance of adaptive antennas and suggests potential solutions to these non-linearity problems in basestation transceiver systems.

### INTRODUCTION:

The evolving standards, such as Future Public Land Mobile Radio Telecommunications System (FPLMTS) in north America and Universal Mobile Telecommunications Systems (UMTS) in Europe [1], for third generation wireless system are placing very demanding requirements upon the air interface specifications. In order to meet the goals of high capacity alongside the support of the full range of tele-services specified for these networks, the integration of adaptive antenna techniques is seen as an attractive solution for the air interface design.

A generic adaptive antenna array, as shown in Figure 1, consists of a number of antenna elements connected together via some form of amplitude and phase control network to form a single or multiple outputs. The amplitude and phase weights (beam forming network) are under the control of a real-time adaptive signal processor, thus the antenna array beam pattern, frequency response and various other parameters can be automatically adjusted in order to enhance the performance of the embedded system. By adjusting the beam former weights,  $N-1$  radiation pattern nulls can be formed towards interfering signal sources, where  $N$  is the number of antenna elements in the array, alternatively, the main beam of the antenna can be electronically steered towards a desired signal

source in order to enhance the antenna's gain in a particular look direction. In addition, the array can be configured to form multiple radiation pattern maxima, or optimise the main beam to sidelobe response. One of the key applications of adaptive antenna arrays considered here is that of spatial filtering in order to separate multiple signal sources, which is sometimes referred to as Spatial Division Multiple Access (SDMA).

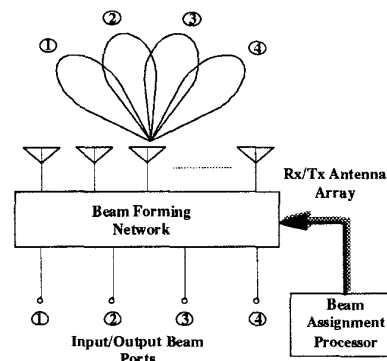


Figure 1: A generic adaptive antenna array system

By exploiting the spatial filtering properties of adaptive antenna arrays in mobile cellular environments it is possible to confine the radio energy associated with a given mobile to a small addressed volume, thus reducing the amount of co-channel interference experienced from and by co-channel users. This ultimately leads to a capacity enhancement for interference limited systems [2]. In terms of UMTS this can be exploited as a capacity enhancement technique, thereby reducing the need for very small cell sizes in traffic hot spot areas, and thus considerably reducing the infrastructure costs and visual impact of the network.

In addition, the adaptive antenna basestation could be used to focus energy towards street canyons where 'black-spots' in system coverage currently exist. This

approach relies upon the exploitation of roof-top diffraction in order to provide the necessary 'in-fill'. In the long term, this approach may eliminate the need for 'Repeaters' in many systems.

The raw throughput of many air interface techniques is limited by the delay spread of the channel. Adaptive antenna techniques can be applied to help combat multipath activity, and thus support higher bit rate services within a given operational environment [3]. This is extremely important in terms of the range of services foreseen for UMTS with data rates of upto 2Mbit/s.

Mobility between different cell types is a necessary prerequisite in UMTS, and thus the umbrella cell has been proposed to support fast moving vehicles within a microcellular service areas, and also support gaps between the service areas offered by the different cell types. However, in order to provide an elegant implementation of seamless handover within a mixed cell environment, all cells types must operate on identical carrier frequencies. This is illustrated in Figure 2. The only foreseeable means of achieving the necessary RF power balancing within each service area, and thus avoiding the near-far effect, is to exploit the spatial filtering properties offered by adaptive antenna systems.

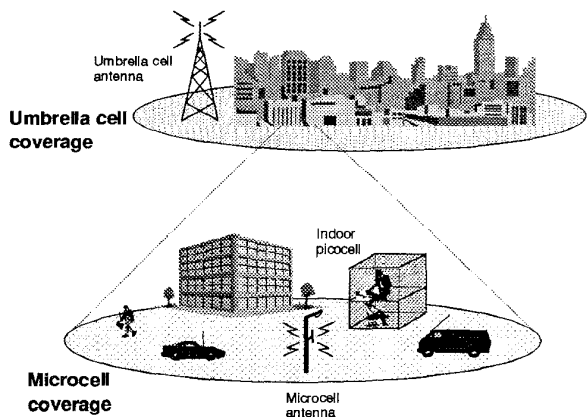


Figure 2: Umbrella cell structure

Despite all these advantages adaptive array antennas offer, their application in commercial mobile communications systems are not common. This was partly due to implementation[4]. Works on feasibility

and system issues are interesting areas, (see for example [5]). This paper addresses the linearity problem in adaptive array antenna implementations.

## LINEARITY REQUIREMENTS IN ADAPTIVE ANTENNA ARRAY SYSTEMS

The beam forming network of an adaptive antenna array can be implemented using either analogue technology at Radio Frequency (RF) or Intermediate Frequency (IF) or Digital circuit technology at Base-band (DB). RF and IF techniques, although once popular, are relatively inflexible when considering the various adaptive antenna architectures suitable for UMTS. The advent of high speed VLSI (Very Large Scale Integrated Circuit) CMOS (Complementary Metal Oxide Semiconductor) digital processing makes this technology suitable for beam forming hardware at DB. However, the use of DB beam forming technique poses high linearity demands on both the RF/IF up- and down-conversion chain. Because the weights of the beam former are carefully constructed at digital base-band, any distortion in the up- and down-conversion chain will alter the antenna beam pattern. Some of the fixed mismatches between channels can normally be calibrated out using on-line calibration techniques. The non-linearity effects in the transceiver chain, however, will cause intermodulation distortion which can not be calibrated out in a practical way. These intermodulation products (IMPs) will ultimately render the adaptive antenna useless. This is illustrated in Figure 3.

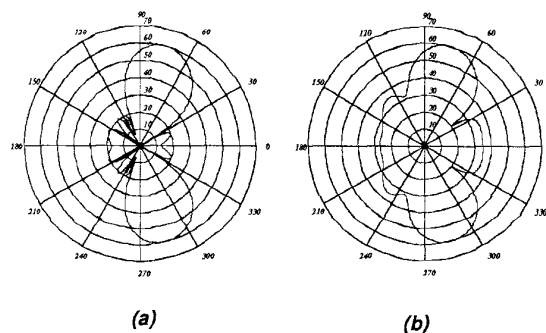


Figure 3: (a) Linear antenna array beam pattern  
(b) the same array with non-linearities present

Here an eight element linear Dolph-Chebyshev weighted antenna array beam pattern is generated with sidelobe level suppressed to be 40dB below the main lobe. In an ideal system, this would mean that in the un-wanted look directions, there is little radiation. However, when some non-linearity is introduced to the system, the antenna beam pattern is severely distorted. Sidelobe levels come back to be just over 20dB below the main lobe. Null depth is reduced with null directions changed. This not only limits the resolution of SDMA but also increases the amount of interfering emissions. It also limits the amount of interference cancellation achievable by an adaptive antenna array system. This effect is clearly not wanted in a adaptive array antenna system.

The relation of IMPs and the antenna amplitude and phase weighting can be shown to be:

$$AMP = \sqrt{1 + \exp(IMP / 10) - 2 \times \exp(IMP / 20) \cos \theta}$$

$$\partial \alpha = \cos^{-1} \left( \frac{1 - \exp(IMP / 20) \times \cos \theta}{\sqrt{1 + \exp(IMP / 10) - 2 \times \exp(IMP / 20) \times \cos \theta}} \right)$$

here,  $IMP = 20 \log(a / b)$ , where  $a$  is the IMP amplitude level and  $b$  is the original amplitude weighting.  $\theta$  is the IMP angle relative to the original weighting vector. These are shown in Figure 4.

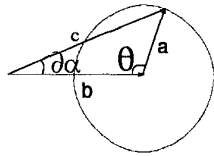


Figure 4: Effect of IMPs

By incorporating the above equations into a simulation program, the effect of non-linearity on linear antenna array parameters, such as side lobe levels (SLLs), null depth (ND), main beam width (BW) and change in null direction (CND), can be derived. Table 1 lists these parameters against different level of IMPs in a transceiver system for an 8 element linear array with Dolph-Chebyshev weighting for a sidelobe level of 30dB below main lobe. It can be seen clearly that with a non-linear system the side lobe level comes up, the null position shifts as well.

The latter has much more serious system implications. This is because when one tries to suppress an interference at a given look direction, the non-linearity in the system will move the null away from the desired direction.

IMP (dB)	BW (°)	SLL (dB)	ND (dB)	CND (°)
-10	11.7	8.7	35.7	9.9
-17	13.3	12.6	29.0	7.4
-20	14.1	15.0	26.2	6.2
-27	15.6	21.4	24.6	2.6
-30	15.9	23.1	25.8	1.7
-75	16.4	29.6	42.5	0

TABLE 1 IMP LEVEL EFFECT

It is also worth noting that the null depth deepens when the IMP level gets high. This is due to the 30dB Dolph-Chebyshev weighting becoming distorted. The SLL is clearly proportional to the amount of IMP level in the system. For comparison an IMP level of 75dB is included in the table as well. It is worth noting that although the BW, SLL and CND do not change much for a system with 30dB IMP level, the ND is reduced from 42.5 to 25.8. The interference cancellation capability is reduced by approximately 50 times (17dB). This will seriously impair the system performance.

The other linearity requirement in a mobile communications system comes from the near-far resistance, or co-/adjacent-channel interference requirement. This is illustrated in Figure 5.

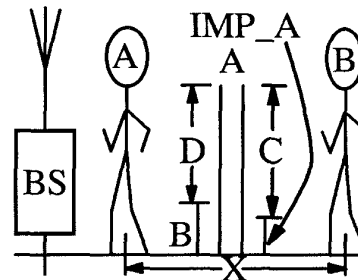


Figure 5: Near-far effects

The IMPs generated by the up- and down- conversion chain tend to drown out the signal from a distant user. The two users, A and B are spatially separated by a distance  $X(m)$  which gives a signal pathloss difference of  $D(dB)$  between A and B. The level of IMPs of the near user, A in this case,  $IMP\_A$  is  $C(dB)$  below the signal level (A) in the system. However,  $IMP\_A$  must be sufficiently lower than that of the far user signal (B) such that user B may establish a successful link. However, if  $D > C$ , the signal from user B will not be demodulated successfully, since  $IMP\_A$  is larger than signal from user B.

The requirement of co-/adjacent-channel protection ratio (CPR/APR) is system dependent (see for example [6-10]). It is therefore difficult to generalise this parameter. However, if a typical CPR/APR of 70dB is used, most un-linearised amplifiers will not meet this specification without sufficient back-off.

In order to fully utilise the potential benefits offered by adaptive antenna array system, the non-linearity effects in the transceiver system will have to be suppressed to a degree such that they will become acceptable.

There are many sources of non-linearity in a transceiver system, such as the up- and down-converters, the amplifiers, and the analogue to digital converter (ADC) and digital to analogue converter (DAC). However, the most crucial part of a transceiver system is the front-end, namely, the low noise amplifier for a receiver and the power amplifier in a transmitter. It is the latter which is deemed most important. It will be the focus of this paper.

## LINEARISATION TECHNIQUES

There are many techniques for amplifier linearisation, such as RF or modulation feedback [11,12], predistortion techniques [13,14], LINC [15,16] (Linear amplification with Nonlinear Components), CALLUM [17] (Combined Analogue Locked Loop Universal Modulator) and Feed Forward Linearisation Techniques (FFLTs) [18-20]. However, not all techniques are suitable for adaptive antenna base station applications. The requirement for an amplifier in a transceiver front-end at a base station is not only

the linearity but also a relatively broad operational bandwidth. The following sections compares these different techniques in turn for their advantages and disadvantages and their suitability in base station applications.

### *Feedback*

Feedback techniques for amplifier linearisation have been established for many years. This approach works by sampling the output of an amplifier and feeding it back to create an error signal such that the system non-linearity will be minimised. The advantage of this technique lies in its implementation: simple and robust. The major disadvantage comes from its structure: being a closed-loop system; its gain-bandwidth product is a constant. This limits its operational bandwidth. This applies to both RF and modulation feed back systems.

### *Predistortion*

This technique used to rely on a pre-knowledge of the amplifier system such that an inverse characteristic of the amplifier can be generated. The combined system response will have a much more linear performance. This classic mode operation, however, has a lot of limitations. The very limited amount of non-linearity cancellation and time-drift are two common disadvantages. New adaptive predistortion techniques [13,14] have much better performance. However, the new system is similar to modulation feedback, it is therefore gain-bandwidth limited. Another problem associated with adaptive predistortion is that the requirement of high speed DSP for relatively large bandwidth [14], which generates the predistortion.

The bandwidth limitation on feedback systems and high speed DSP requirement for predistortion system coupled with limited amount of IMP cancellation make these two techniques unsuitable for base station applications.

### *LINC and CALLUM*

CALLUM [17] is essentially a kind of LINC [15,16] system. This class of linearisation techniques have considerable potential for high efficiency linearised

transceivers. The system operates by splitting a signal into two constant envelope phase modulated signals, which are then amplified using highly efficient non-linear amplifiers. The output from these two paths are then combined together to form an amplified version of the input signal. The key points are therefore: signal generation, matched amplification and efficient combination for LINC to be successful. CALLUM partially solved the first two problems over a narrow operational bandwidth. LINC system overall as a technique still awaits further development.

#### *Feed Forward Linearisation Techniques*

This technique was introduced for amplifier linearisation nearly thirty years ago [18]. But different researchers, especially [19,20], have made various improvements to make this technique a much more robust, stable and truly broadband technique. This makes feed forward linearisation techniques a very suitable candidate for mobile communications applications, especially at the base stations where transceiver operates in multiple carrier mode.

A schematic of a feed forward amplifier (FFA) is shown in Figure 6.

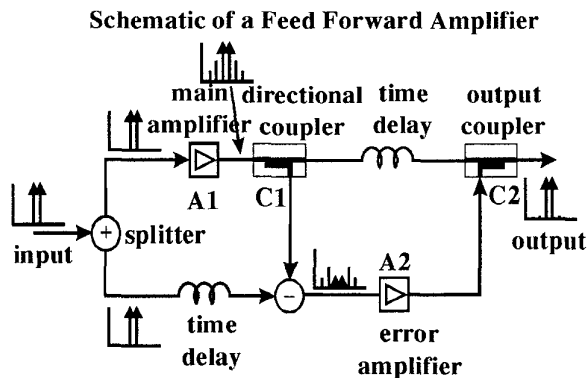


Figure 6: A feed forward amplifier system

Its operation can be followed by referring to the two-tone test spectra shown at various points throughout the diagram. Here an input two-tone signal is splitted into two path: for amplification (A1) and reference. The output from the main amplifier A1 is sampled by coupler C1 and then compared with the delayed reference signal. The resultant error signal is

amplified by an error amplifier A2 which is then combined with the delayed output signal from A1 at coupler C2. When the error signal is matched with the output signal, the IMPs will be cancelled out completely in theory. The operation of a FFA is open loop. It is therefore inherently stable across a broad signal bandwidth.

Some earlier work carried out in the Centre for Communications Research, University of Bristol [19,20] have achieved better than 80dB IMP free dynamic range feed forward amplifier system at 900MHz. Work is being carried out to constructed FFAs at the UMTS frequencies.

The effect of a large linear dynamic range transceiver system has a number of significant implication on communications systems. First of all, it will allow an adaptive antenna system to work to its best possible performance. This will not only extend the range of coverage of a mobile base station; it will also improve the overall system performance. Recent simulation work [21] has shown that with the use of an adaptive array antenna, the RMS delay spread can be reduced by a factor of 3. This in most practical systems will eliminate the need of a channel equaliser. Secondly, it will make dynamic frequency allocation possible, which will enhance network performance tremendously. It will also permit the use of linear modulation format which will improve system capacity even further.

#### **CONCLUSIONS AND DISCUSSIONS**

The effects of non-linearity on the performance of adaptive array antennas has been presented. Techniques on amplifier linearisation has been reviewed. The feed forward technique is identified as the most suitable for mobile communication base station applications. This is because that the large bandwidth requirement and multiple carrier operations at base stations. The effect of using linearised amplifiers in communications system has also been discussed.

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